INFRARED SURFACE TEMPERATURE MEASUREMENTS IN NAVSWC'S HYPERVELOCITY WIND TUNNEL NO. 9

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ABSTRACT

This paper will describe recent efforts at the Naval Surface Warfare Center's Hypervelocity Wind Tunnel No. 9 to measure wind tunnel model surface temperatures using a commercially available infrared (IR) camera. IR camera measurements on a Macor model surface tested at Mach 14 in Tunnel 9 will be presented and the data will be compared to vapor-deposited thermocouple measurements made on the same substrate. The IR data was collected using an InfraMetrics Model 600 Infrared Camera and has been reduced using the camera manufacturer's software. The results of this analysis will show the feasibility of making global non-intrusive heat transfer measurements using an infrared camera.

NOMENCLATURE

M = Mach number
P = Pressure
Re/L = Free stream Reynolds number/ft
s = Signal measured by the IR camera
T = Temperature
τ = Transmittance of IR radiation, optically
W = Radiant energy
e = Emittance
σ = Stefan-Boltzmann constant
Δ = Difference between current and initial value

Subscripts

B = Background
c = Signal Camera observes
o = Supply
s = Target/Model true Surface

INTRODUCTION

A commercially available infrared (IR) imaging system, the InfraMetrics Model 600, is being evaluated to support heat transfer testing in the Naval Surface Warfare Center's (NAVSWC) Hypervelocity Wind Tunnel No. 9. The objective of this developmental effort is to determine the ability of this non-intrusive optical system to make global surface temperature measurements on wind tunnel models. This method can be useful to produce global, high definition, heat transfer data as opposed to point measurements obtained from standard heat transfer gages. Infrared temperature measurements have been made on a Macor panel, a Corning brand machinable mica glass ceramic, mounted in a thin wing of an aerodynamic body configuration which was tested at Mach 14. A description of the test program, the results obtained, and conclusions are outlined in this paper.

THE INFRARED IMAGING SYSTEM

The InfraMetrics Model 600 camera is a scanning radiometer with a single Mercury-Cadmium-Tellurium detector. The detector operates in the 8-12 micron wave band and is cooled to 77 K with liquid nitrogen to minimize detector noise. The response time of this detector is on the order of 160 nanoseconds. An image of the observed target is opto-mechanically scanned across the detector to create a complete IR image. The scanning process is accomplished by using a horizontal and vertical scanning mirror, each driven by a galvanometer. This process directs radiation through a focusing lens and onto the detector. The camera sample rate is 30 frames or 60 fields per second where each frame is constructed of two interlaced consecutive...
fields. Data acquired with the IR camera differs from data obtained from a standard video camera, which has a staring array which samples all pixels at the same time. IR Camera images are constructed of data scanned at different points in time and a controller processes and prepares the detector signal for display on a typical video system in either black-and-white or color. The displayed image consists of 200 rows of data with each row containing 256 pixels.

The equation governing the emission of infrared radiation from an object is the modified version of the Stefan-Boltzmann Law for real objects.

\[ W = e\sigma T^4 \]  

This equation shows the radiant energy emitted, \( W \), to be related to the fourth power of temperature through \( \sigma \), the Stefan-Boltzmann constant, and \( e \), the emittance of the object. An emittance value of \( e = 1 \) defines the theoretical blackbody, and a value of \( e = 0 \) defines the perfect reflector. For wind tunnel models, the emittance is a function of model material, material finish, angle at which the model is viewed, the temperature of the model, and the wavelength of radiation being detected. The emittance must be known in order to make quantitative temperature measurements.

**FACILITY DESCRIPTION**

The NAVSWC Hypervelocity Wind Tunnel No. 9 is shown in Figure 1. It is a blow-down facility which operates at Mach numbers of 10 and 14 and Reynolds numbers ranging from 8.5\( \times 10^6 \) to 2.0\( \times 10^7 \) per foot at Mach 10 and from 7.5\( \times 10^6 \) to 4.0\( \times 10^6 \) per foot at Mach 14. The test cell is five feet in diameter and over twelve feet long, which allows the testing of large model configurations.

Tunnel 9 uses nitrogen as the working fluid. During a typical run, the vertical heating vessel is used to pressurize and heat a volume of nitrogen to a predetermined pressure and temperature. The test section and vacuum sphere are evacuated to a low pressure and are separated from the heater by a pair of metal diaphragms. When the nitrogen in the heater reaches the proper temperature and pressure, the diaphragms are ruptured and the gas flows from the top of the heater and expands through the nozzle. As the hot gas exits the heater, cold gas from three pressurized driver vessels enters the heater base. The cold gas drives the hot gas at a constant pressure in a piston-like fashion, thereby allowing constant supply conditions to be maintained for the entire period in which "good flow" exists. More detailed information on Tunnel 9 can be found in References 1 and 2.

**TEST MODEL AND CONDITIONS**

The model tested during this development effort was a full-body aircraft configuration. The area of interest to the IR Camera development was a Macor panel that was mounted on the wing of a wind tunnel model. The Macor panel, a machinable ceramic, was mounted in the wing of the model and served as a substrate for vapor-deposited, iron-nickel thermocouples. These gauges were used because the wing was too thin to mount conventional coaxial thermocouples. The panel was triangular in shape and was instrumented with nine vapor-deposited thermocouples, as shown in Figure 2.

During this experiment the wind tunnel model was pitched from 0° to -2° to +14° angle of attack. The average tunnel conditions for this experiment were:

- \( M = 14 \)
- \( P_e = 19000 \text{ psi} \)
- \( T_e = 2700 \text{ °F} \)
- \( \text{Re}/L = 3.8 \times 10^6/\text{ft} \).

**SYSTEM SET-UP**

The IR camera viewed the model/target from above as shown in Figure 3. The camera is mounted underneath a photographic tripod in the vertical position. This is made possible by the use of an external liquid nitrogen feed dewar. The feed dewar is equipped with a flexible tubing interface with the camera dewar, providing a supply of liquid nitrogen to the camera dewar to cool the detector, while allowing the camera to be mounted at any angle up to 90° (vertical). A vertical camera position is desirable in order to eliminate all unnecessary signal degradation due to additional optics.
The external dewar also gives the camera a liquid nitrogen hold-time of up to two hours. This is necessary because of the time differential between when the tunnel room is closed and when the tunnel run occurs. The camera views the model through a 4" diameter by 1/2" thick, zinc selenide window. This window has a broad band anti-reflection coating on both surfaces giving it a transmittance in the 8-12 micron range ≥ 96%.

The camera is controlled remotely from the tunnel control room where final firmware adjustments can be made just prior to a tunnel run. The black and white video data signal is also routed from the top of the test cell to the control room. This signal then is passed through an IRIG time code generator and into a Panasonic AG-2400 VCR. The signal is recorded on standard 1/2 inch (VHS) video cassettes and is played back for analysis. During the tunnel run the camera was set in the "Data Acquire" mode with the emittance set to 1.0. This allows the cleanest possible signal to be recorded by removing all extraneous graphics from the image. It is also important to record the data with the emittance function set to 1.0 so the proper corrections can be made to the signal during data reduction. If an incorrect value for surface emittance is entered, then retrieving the actual signal values is very difficult or impossible.

DATA COLLECTION AND REDUCTION

The data is stored on VHS tape and is played back into the video image processing work-station for analysis and reduction. The work-station consists of an IBM AT equipped with a ThermaGRAM board and ThermoTeknix software provided by the camera manufacturer, Inframetrics, to decode and interpret the images on the VHS tape. The software allows field formatted images to be frozen, digitized and stored on disk from live or video playback signal. The freezing function is not automated, thus there is no ability to capture successive fields of video. This results in an uneven or random time step between samples of data or images.

The camera detector records the intensity of radiation emitted from the surface and attenuated by the window. The camera is set up to make no corrections and converts the intensity levels to temperatures as if the surface was a blackbody. The intensities are converted using a calibration table look-up which is stored in the camera controller firmware.

Once the signal intensity is converted to a blackbody equivalent temperature the optics and surface emittance corrections can be made. The temperature recorded by the camera (\(T_J\)) is represented by the following equation:

\[ T_s = \tau (T_r \cdot e + T_b(1 - e)) \]  

Equation 2 is solved for the surface temperature \(T_r\):

\[ T_r = T_s/(\epsilon \cdot \tau) - T_b(1 - \epsilon)/\epsilon \]  

The temperature rise equation is shown as follows:

\[ \Delta T_s = \Delta T_p/(\epsilon \cdot \tau) - \Delta T_b(1 - \epsilon)/\epsilon \]  

Temperature rise data is required to perform 1-D semi-infinite slab heat transfer analysis.

The stored images are read back into the Thermoteknix program and blackbody equivalent temperatures (\(T_s'\)s) were sampled at different thermocouple locations on the image. This was a tedious process for this test because the model was pitching, and thus, the image of the wing was changing position and size and the exact locations of the thermocouples were unknown. The absolute blackbody equivalent temperatures from each field of IR data at four thermocouple locations, T69, T70, T72, and T74, were sampled by hand and input into a data base. The IR data was then converted to temperature rise data and was then corrected for the surface emissivity (\(\epsilon\)) and the external optics transmission factor (\(\tau\)). The emissivity of Macor\(^4\) is 0.79 and the window transmittance was assumed to be 0.97 for all points. The background temperature increases a maximum of 4°F during a tunnel run. This maximum \(\Delta T_b\) accounts for approximately 1°F difference in the final measurement of temperature rise. This temperature rise was neglected, thus equation (4) reduces to:

\[ \Delta T_s = \Delta T_p/(\epsilon \cdot \tau) \] (5)
where \( 1/(e^\tau) = 1.3 \).

The temperature rise data from the vapor-deposited thermocouples were also transferred to the same data base for comparison as a standard.

The \( \Delta T \) calculations for the IR camera were then compared to the thermocouple temperature rise data for gauges T69, T70, T72 and T74 as shown in Figures 4 - 7. The figures show reasonable agreement between the two sets of data. The scatter of the IR data is believed to be largely a result of the fact that the model was moving and the exact location of the thermocouples, in the image, was unknown.

A heat transfer analysis was not performed because the properties of the Macor panel vary greatly with temperature. Standard 1-D or 2-D heat transfer analysis require constant material properties; thus this analysis was not done. A heat transfer analysis of the IR data also would have been hampered because of the inability to capture evenly spaced data in time. Again, standard heat transfer algorithms require evenly spaced data samples. Curve fitting techniques can be used but without the redundant thermocouple measurement, fitting a curve of unevenly spaced transient data, in order to calculate heat transfer with reasonable accuracy, would be difficult.

RESULTS

A run was made in Tunnel 9 where the IR camera measured the temperature rise on the surface of a flat Macor panel mounted in a thin wing. This data was compared with the vapor-deposited thermocouple data as shown in Figures 4-7. All the figures show reasonable agreement but with significant scatter, greater than \( \pm 5\% \) of the measured value. The IR data follows all the same trends as the thermocouple data. The figure with the best agreement, Figure 6, shows nearly all the IR data within a band of \( \pm 5\% \) of the measured thermocouple data.

SOURCES OF ERROR

The differences and scatter between the two measurement sets can possibly be explained by the following sources of error that have been identified.

The first source of error in this experiment was the inability to find the exact location of the thermocouples in the IR image. The exact location, which is necessary for comparison of the two measurements, had to be inferred from comparing the position of thermocouples on the Macor panel to the size of the panel in the IR image. The error was compounded by the angle of attack sweep of the model which caused the image to move. As a result, the thermocouple locations were not known exactly and this location changed throughout the run.

The emissivity of the Macor surface is not well known. The emissivity of Macor has been measured in an IR spectrometer and was determined to have an average emissivity of 0.79 between 8 - 12 \( \mu \text{m} \). This is an accurate measurement but it was not taken with a substrate from our model or the material lot from which it was machined. This error is believed to be small.

As previously stated, the background temperature can be ignored if it does not change and this is known not to be true. The background temperature has been measured using coaxial thermocouples. These thermocouples show a rise of approximately 4\(^\circ\text{F} \) at the locations shown in Figure 3. This temperature rise needs to be accounted for when the heat transfer data reduction method is finalized but has been neglected in this analysis.

The emissivity of surface emissivity is another possible source of error. Small variations in surface emissivity are not accounted for in the reduction, but are believed to be insignificant, less than \( \pm 2\% \) in surface emissivity. The actual vapor deposition could have changed the emittance in the vicinity of the gauge. If the image was sampled at the exact vapor locations the emittance may have been different, adding to the scatter of the data.

The transmittance of the window is quoted as 96\% or greater by the manufacturer but has never been independently measured. The high level of transmittance is dependent on the broad-band anti-reflection coating on the surface of the window. This coating may vary or deteriorate with use in the wind tunnel environment.
CONCLUSION

This experiment has proven to be very beneficial in advancing the efforts at the Naval Surface Warfare Center to develop a non-intrusive temperature measurement technique. Past data collected on metal models in Tunnel 9 with low emissivities, on the order of $e = 0.3$, produced no useful quantitative results. The results of this recent test have confirmed the theory that the target must have a high emissivity, approximately 0.80 or greater, in order to make meaningful measurements. In order to solve this problem, research has been undertaken to find a surface coating that increases the surface emissivity of metal (stainless steel and aluminum) without changing its thermal properties. This would allow IR cameras to make accurate temperature and heat transfer measurements.

Global heat transfer measurements of the surface is the ultimate goal for the system. This can be achieved with temperature rise data. Absolute temperature data are not necessary. This simplifies the data reduction and verification since standard wind tunnel temperature measurement gauges (coaxial thermocouples) measure temperature rise and not absolute temperature without a reference junction.

Software with the capability to capture successive fields of video data has recently been procured. With the implementation of this ability, complete data sets can be generated in the future.

Software is also being generated to handle the large amounts of data necessary to produce global heat transfer data for the full images of data. This software will have the ability to automatically decode and process consecutive images of data, applying the proper corrections for emissivity, optical transmittance and background temperature. The result will be global temperature rise data and ultimately heat transfer data.

The completion of this software along with the ability to produce a known, high surface emissivity will make global, non-intrusive heat transfer a reality in Tunnel 9.

References


FIGURE 1. NAVSWC HYPERVELOCITY WIND TUNNEL NO.9

FIGURE 2. MACOR PANEL INSTRUMENTATION LAYOUT

Vapor-Deposited Thermocouple

All Dimensions in cm.
Wind Tunnel

External Feed Dewar

Control Room

FIGURE 3. IR CAMERA SET-UP

Gauge T69

Delta Temperature (deg F)

0.000 0.200 0.400 0.600 0.800 1.000 1.200

Time (Sec.)

FIGURE 4. IR DATA VS. THERMOCOUPLE DATA
FIGURE 5. IR DATA VS. THERMOCOUPLE DATA

FIGURE 6. IR DATA VS. THERMOCOUPLE DATA
FIGURE 7. IR DATA VS. THERMOCOUPLE DATA